TPH 0840

Engineering Training Publication

Magnetism And Electro - Magnetism - ETP 0300

Issue 1, 1970

Prepared by:
Engineering Training.

Authcrised by:
Manager,
Operations Planning and Programming Branch, HQ.

Distribution Code: Selective
Filing Category: K

Telecom Australia

Telecom Australia
ENGINEERING TRAINING
210 Kingsway, South Melbourne. 3205

Training
PUBLICATIONS
ETP 0300

MAGNETISM AND ELECTROMAGNETISM

PUBLISHED 1970
(PREVIOUSLY RGP 003)

Page

1. INTRODUCTION 1
2. EFFECTS OF MAGNETISM 2
3. ELECTROMAGNETISM 6
4. TERMS USED IN MAGNETISM 9
5. FERROMAGNETISM 11
6. MAGNETIC MATERIALS 16
7. INDUCED E.M.F's AND CURRENTS 18
8. GENERATORS 22
9. MOTORS 25
10. INDUCTION AND INDUCTANCE 29
11. TRANSFORMERS - SIMPLE THEORY 31
12. TEST QUESTIONS 38

1. INTRODUCTION

1.1 Early students of science believed that magnetism and electricity were separate phenomena. However, discoveries made in the early part of the nineteenth century showed the two to be directly related. This has been verified by modern science, and it is now generally believed that magnetism and electricity have a common origin in the atoms which make up all matter.

1.2 Magnetism plays an important part in many items of electrical apparatus. In a modern household, the principles of magnetism are applied in all types of motorised appliances as well in the loudspeakers in TV and radio receivers. In telecommunication, the applications of magnetism cover a wide variety of equipment items ranging from the telephone receiver to the memory unit in computer equipment.

1.3 This paper reviews general aspects of the behaviour and characteristics of permanent and electromagnets. It describes the process by which iron becomes magnetised, and gives details of the characteristics of the magnetic materials used. This paper also examines the principles and laws of electromagnetic induction and their application to telecommunication.

E.T.S. 12/0524

2. EFFECTS OF MAGNETISM

2.1 A magnet is a substance which attracts or repels certain other substances. The attracting and repelling property of a magnet is called magnetism, and a substance which possesses this property is said to be magnetised.

2.2 MAGNETIC MATERIALS. Materials which can be readily magnetised are called magnetic materials. Magnetism is most noticeable in iron and steel, but often, small amounts of nickel, chromium, cobalt, tungsten and other materials are added to iron to make special alloys which have magnetic properties suitable for different applications.

Other substances, such as brass, copper, aluminium, zinc and glass are practically non-magnetic. These substances however, allow magnetism to pass without themselves becoming magnetised to any extent.

2.3 MAGNETS. Magnets can occur naturally as pieces of iron ore which are found in a magnetised state, or they can be produced by artificial means. Where natural magnets are weak and irregularly magnetised, artificial magnets are relatively strong and can be magnetised as desired. All magnets used in telecom equipment are artificially produced and these can be of two kinds. These are:

- PERMANENT MAGNETS, which keep their magnetism for a long period of time unless subjected to demagnetising forces such as heat or jarring. Modern permanent magnets are usually cast from special iron alloys, or moulded from special non-metallic materials called ferrites.

- TEMPORARY MAGNETS, which quickly lose their magnetism when the magnetising force is removed. These usually are made from soft (magnetically) iron, or from alloys of iron with nickel, cobalt or vanadium. Many temporary magnets derive their magnetism from the magnetic effects of electric current and are called electromagnets.

Both types of magnets are used extensively in telecom equipment, and these are made in a variety of strengths, shapes and sizes. With metallic magnets, the most commonly used shapes are bars and horse shoes, while non-metallic magnets can be obtained as blocks, bars, rods, cylinders, discs or rings.

2.4 MAGNETIC POLES. The force of attraction or repulsion exhibited by a magnet is not uniform, but is concentrated at certain points called magnetic poles. Most magnets have two poles located on opposite faces of the magnet. The part of the magnet midway between the poles exhibits little or no magnetism and is called the neutral zone. These regions are indicated in Fig. 1 which shows the effect of dipping a bar magnet into a pile of iron fillings.

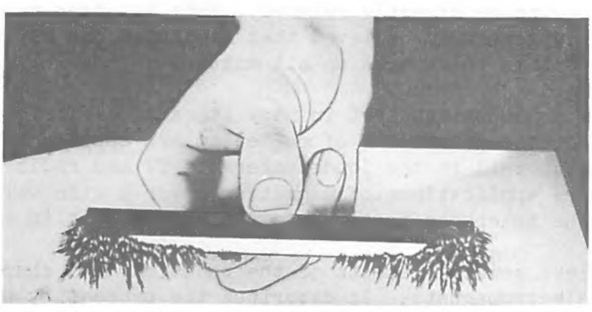


FIG. 1. MAGNETIC POLES.

When a magnet is freely suspended, it aligns itself with the magnetic poles of the earth. This principle is applied in the magnetic compass, which is merely a small bar magnet pivoted on a sharp point.

The magnet pole which points to the north under these conditions is called the "north-seeking" pole, or more commonly, the north pole. The pole which points to the south is called the "south-seeking" pole, or the south pole.

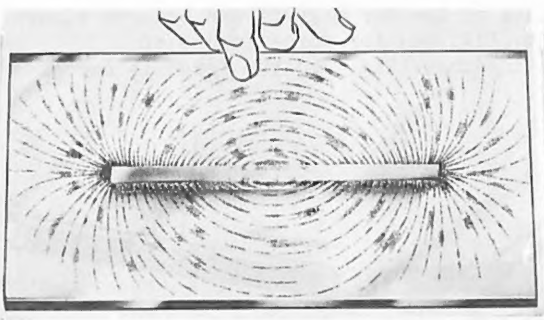
2.5 MAGNETIC FIELDS. Magnetism is an invisible force and can only be seen in terms of the effects it produces. The space in the vicinity of a magnet, in which the forces of attraction and repulsion are apparent, is called a magnetic field.

To assist in the understanding of magnetic effects, magnetic fields are usually represented by lines drawn to show the area of influence of the magnet. These lines are called lines of force.

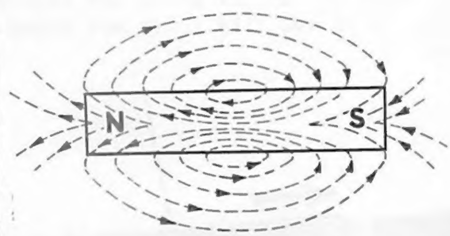
By convention, it is assumed that the lines of force leave the magnet at the north pole, travel through the surrounding space to re-enter at the south pole. The lines of force then travel inside the magnet from the south pole to the north pole to complete closed loops. Each closed loop tends to be as short as possible, but as loops repel adjacent loops, they never cross.

2.6 FIELD PATTERN FOR A BAR MAGNET. The pattern and arrangement of these lines of force can be traced out by moving a compass needle around a magnet, or by sprinkling iron filings on a glass plate or a piece of paper on the top of the magnet. The filings form a regular pattern when the glass or paper is gently tapped.

The magnetic field pattern obtained in this way for a bar magnet is shown in Fig. 2a. The conventional method of representing this field by lines of force is shown in Fig. 2b.



(a) Pattern with Filings.

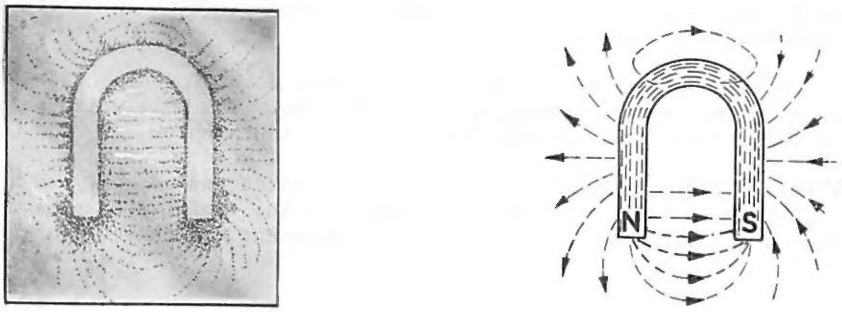


(b) Pattern With Lines of Force.

FIG. 2. MAGNETIC FIELD OF BAR MAGNET.

2.7 FIELD PATTERN FOR A HORSESHOE MAGNET. A horseshoe magnet is essentially a bar magnet which has been formed into a horseshoe shape so that the poles are adjacent. This shape concentrates the field inside the horseshoe at the end of the magnet as shown by Fig. 3a.

The magnetic field pattern for a horseshoe magnet as represented by lines of force in the conventional manner is shown in Fig. 3b.



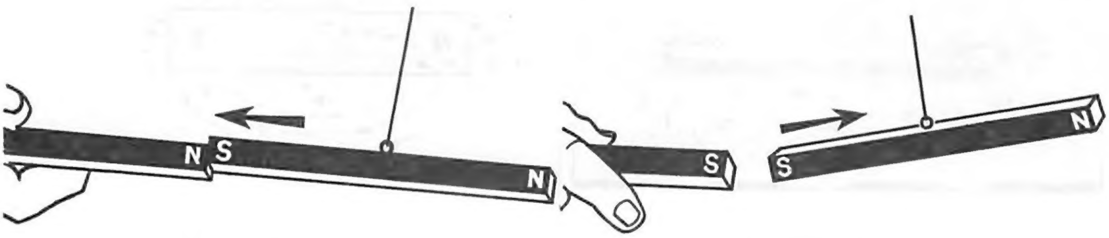
(a) Pattern With Filings. (b) Pattern With Lines of Force.

FIG. 3. MAGNETIC FIELD OF HORSESHOE MAGNET.

The idea of lines of force is simply a convenient assumption to help in the understanding of the behaviour of magnets and magnetic substances. Although diagrams of magnetic fields usually represent the lines of force in one plane, it must be remembered that the force of the magnetic field acts throughout the whole of the space surrounding the magnet, and not just along these imaginary lines.

2.8 ATTRACTION AND REPULSION OF MAGNETIC POLES. By observing the reaction of a freely suspended magnet towards an adjacent magnet, it can be seen that the two poles of a magnet are unlike. For example, when a compass needle is placed in different positions near a bar magnet, the north pole of the needle is always attracted to the magnet's south pole but repelled by the magnet's north pole. The south pole of the needle is always attracted to the north pole of the magnet, but repelled by the south pole.

The same effects can be observed when the poles of two bar magnets are brought close together. When two unlike poles are adjacent (Fig. 4a) the force is one of attraction; when two like poles are brought together (Fig. 4b) the force is one of repulsion.

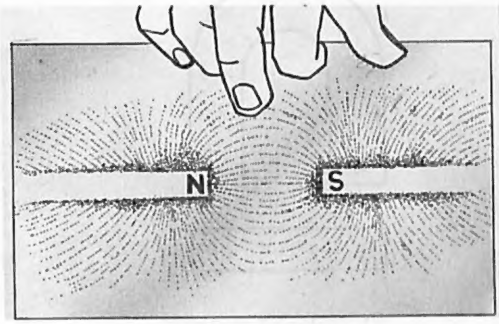


(a) Attraction. (b) Repulsion.

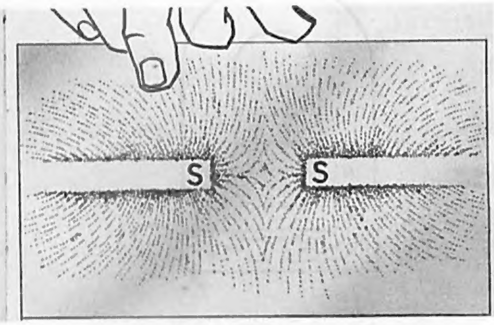
FIG. 4. FORCES BETWEEN MAGNETIC POLES.

This attraction or repulsion between the poles is due to the aiding or opposing of the lines of force of the magnets. For example, when two bar magnets are placed end to end, and iron filings are used to map out the lines of force, the effects are shown in Fig. 5.

With unlike poles (Fig. 5a), the lines of force from each magnet link up and tend to draw the poles together so that the magnets attract one another. With like poles (Fig. 5b), the lines of force are crowded and tend to push the poles apart, so that the magnets repel.



(a) Unlike Poles.



(b) Like Poles.

FIG. 5. MAGNETIC FIELDS OF ADJACENT MAGNETS.

Experiments have been conducted to determine the magnitude of the forces exerted between adjacent magnetic poles. These experiments have shown that the force of attraction or repulsion depends upon the strengths of the poles and distance between them.

2.9 LAWS OF MAGNETISM.

The effects observed when magnetic poles are brought near to one another are summarised in statements which are known as the Laws of Magnetism.

The Laws state:

- *Like poles repel and unlike poles attract.*
- *The force of attraction or repulsion between two magnetic poles is directly proportional to the product of their pole strengths, and inversely proportional to the square of the distance between them.*

The second law can be expressed mathematically as:

$$F \propto \frac{M1 \times M2}{d^2}$$

where

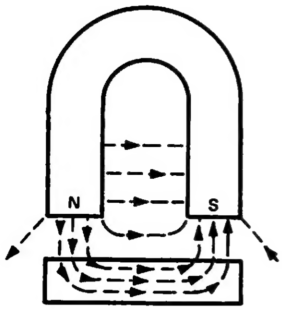
F = Force of attraction or repulsion;
M1 = Strength of pole 1;
M2 = Strength of pole 2;
d = Distance separating the poles.

2.10 MAGNETIC INDUCTION.

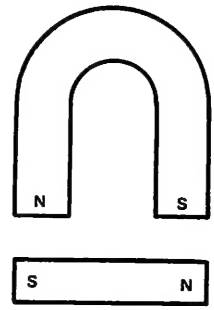
When a magnet is brought near to an unmagnetised piece of magnetic material such as iron, the iron is attracted to it. Since attraction only occurs between unlike magnetic poles, it is reasonable to assume that the piece of iron becomes magnetised when the magnet is brought near to it. This process is called magnetic induction.

Fig. 6a shows a horseshoe magnet adjacent to a small iron bar. The lines of force from the magnet travel through the bar, producing poles at its extremities. The lines of force enter the iron opposite the north pole of the magnet, travel the length of the bar, and leave at the end opposite the magnet's south pole.

We saw earlier, that within a magnet, lines of force travel from south to north. This means that the induced poles in the iron bar are opposite in polarity to those causing the induction. These polarities are shown in Fig. 6b.



(a) Path of Lines of Force.



(b) Induced Poles.

FIG. 6. MAGNETIC INDUCTION.

The process by which a magnet attracts pieces of magnetic material can be summarised as follows:-

- the magnet induces poles of opposite polarity in the material;
- attraction occurs in accordance with the laws of magnetism.

2.11 RESIDUAL MAGNETISM. When a piece of magnetic material has been magnetised by induction, it usually retains some of the induced magnetism after the magnet has been taken away. The amount of magnetism which remains after the magnetising force has been withdrawn is called the residual magnetism.

The ability of a magnetic material to retain residual magnetism is sometimes called retentivity.

2.12 MAGNETIC SCREENING. In telecom equipment, it is often necessary to prevent magnetic fields from affecting nearby apparatus. This is achieved by placing a magnetic screen around the apparatus to be shielded, or by placing a magnetic screen around the source of the interfering magnetic field.

The principle of magnetic screening is shown in Fig. 7. The apparatus requiring screening is enclosed in an iron can or case so that most of the lines of force travel through the iron which provides an easier path than does air. The effectiveness of the screen depends upon the thickness of the case, and the magnetic characteristics of the iron from which it is made.

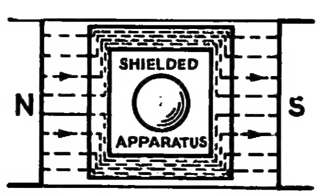


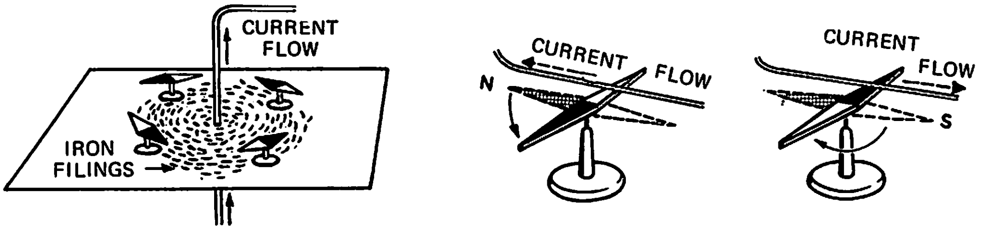
FIG. 7. MAGNETIC SCREENING.

3. ELECTROMAGNETISM

3.1 In the early part of the nineteenth century, a Danish physicist named Hans Christian Oersted discovered that a magnetic field is produced when an electric current flows in a conductor. The relationship between electricity and magnetism is called electromagnetism, and many items of telecom equipment rely on this effect for their operation.

3.2 MAGNETIC FIELD ABOUT A CURRENT-CARRYING CONDUCTOR. A number of simple experiments can be conducted to detect the presence of a magnetic field around a current-carrying conductor. For example:

- When a wire carrying a current is buried in iron filings and then lifted, it is found that some of the filings cling to its surface. When the current through the wire is increased and the experiment repeated, more filings cling to the wire. When the current is stopped the filings fall from the wire.
- When the same piece of wire is passed through a hole in a horizontal piece of cardboard and iron filings are sprinkled on the card, the iron filings take up a pattern of concentric rings when current flows and the card is tapped. (Fig. 8a).
- When a compass needle is placed near to a conductor carrying a current, the needle is deflected at right angles to the wire. When the direction of current is reversed, the compass needle swings in the opposite direction (Fig. 8b).



(a) Field Pattern. (b) Compass Needle Deflects.

FIG. 8. THE MAGNETIC FIELD DUE TO ELECTRIC CURRENT.

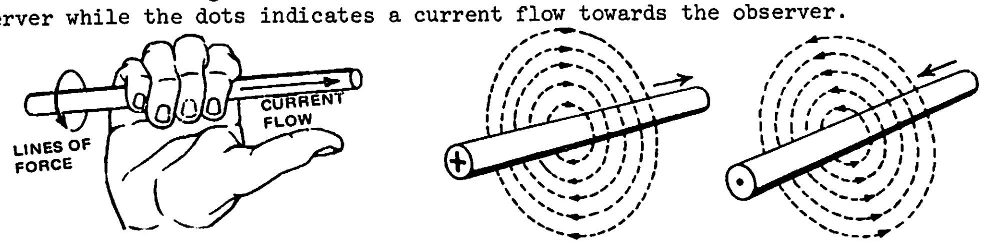
The results of these simple experiments can be summarised as follows:

- the strength of the magnetic field around a current-carrying conductor depends upon the value of the current;
- the field takes the form of concentric rings in a plane at right angles to the conductor;
- the direction of the magnetic field depends upon the direction of the current.

3.3 THE RIGHT-HAND RULE. The direction of the magnetic field surrounding a current-carrying conductor can be determined from the right-hand rule. The rule states:

If the fingers of the right hand are placed around the wire so that the thumb points in the direction of current flow, the fingers point in the direction of the magnetic field.

The method of applying this rule is shown in Fig. 9a. The result of its application to current-carrying conductors is shown in Fig. 9b. The cross at the end of the conductor in the diagram indicates a current flow (conventional) away from the observer while the dots indicates a current flow towards the observer.



(a) Right-Hand Rule. (b) Direction of Fields.

FIG. 9. THE RIGHT-HAND RULE.

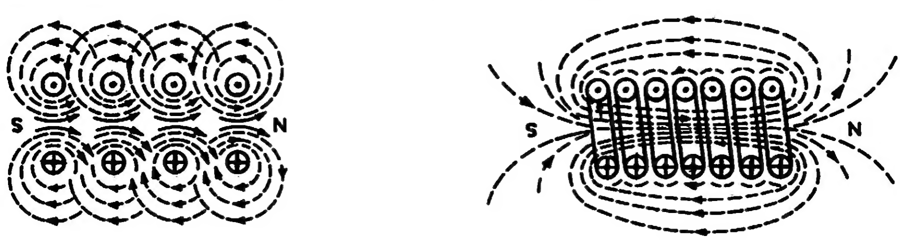
3.4 MAGNETIC FIELD OF A LOOPED CONDUCTOR. The comparatively weak magnetic field surrounding a straight conductor can be intensified when the conductor is formed into a single turn or loop. When current flows in the loop the lines of force surrounding the conductor pass through the centre of the loop as shown in Fig. 10a.

When the right-hand rule is applied, the direction of the lines of force can be established. In Fig. 10b, it can be seen that within the loop, the lines of force are in the same direction, and are more concentrated than in the area outside the loop.

(a) Current-Carrying Loop. (b) Magnetic Field.

FIG. 10. MAGNETIC FIELD OF A LOOPED CONDUCTOR.

3.5 MAGNETIC FIELD OF A SOLENOID. A solenoid consists of many turns of insulated wire, wound close together in the form of a coil. When current flows in a solenoid, the magnetic field produced by each turn interacts with that produced by adjacent turns, as shown in Fig. 11a. Within the solenoid the lines of force are in the same direction so that the resultant field is as shown in Fig. 11b. This corresponds to the field pattern of a bar magnet, possessing a North pole where the lines of force leave the coil, and a South pole where they enter.



(a) Fields Interact. (b) Resultant Magnetic Field.

FIG. 11. MAGNETIC FIELD OF A SOLENOID.

The strength of the magnetic field of a solenoid depends upon the number of turns in the coil and the value of the current flowing, and an increase in either of these, results in an increase in field strength. The strength of the field can also be increased by the inclusion of an iron core in the coil, which has the effect of concentrating the magnetic field.

3.6 THE RIGHT-HAND RULE FOR SOLENOIDS. The direction of the magnetic field produced by a solenoid can be determined by applying the right-hand rule for solenoids. The rule states:

When the fingers of the right hand are wrapped around the coil in the direction of the current flow, the thumb points to the north pole end of the coil.

The method of application of this rule is shown in Fig. 12. When the polarity of the magnetic field is known, the direction of the current flow can be determined by using the same rule.

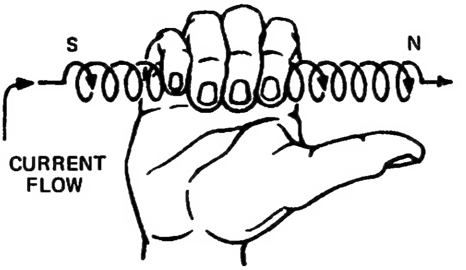


FIG. 12. THE RIGHT-HAND RULE FOR SOLENOIDS.

4. TERMS USED IN MAGNETISM

4.1 In the study of magnetism, certain terms are commonly used to describe the various quantities and conditions that exist. These terms have application to all types of magnetic fields, irrespective of whether they are produced by permanent magnets or by electromagnets.

4.2 **MAGNETIC FLUX.** The total number of lines of force entering or leaving the pole of a magnet is called the magnetic flux. The same term can be applied to the total number of lines of force induced into a magnetic material.

The symbol for magnetic flux is the Greek letter "phi", which is written as ϕ. The unit for magnetic flux is the WEBER. The precise definition of the weber requires a knowledge of factors not yet considered. However, one weber is equivalent to 10^8 lines of force.

4.3 **FLUX DENSITY.** In determining the state of magnetisation of a substance, it is often more important to know the density of the magnetic flux rather than the total flux. For example, a certain value of flux when concentrated in a sample of small cross-section, represents a greater intensity of magnetisation than does the same flux when spread over a larger area.

The flux density of a magnetic material is a measure of the magnetic flux per unit area, measured at right angles to the direction of the magnetic field. The symbol for flux density is B, and the unit for flux density is the TESLA. One tesla is equal to one weber per square metre.

4.4 **MAGNETOMOTIVE FORCE.** The total force which establishes and maintains a magnetic flux is called the magnetomotive force, the symbol for which is F. To a degree, the magnetomotive force is similar in effect to the electromotive force in an electric circuit.

Magnetomotive force is measured in terms of the force produced when an electric current flows in a conductor. When the conductor is formed into a coil, the magnitude of the force depends upon the value of the current, and the number of terms. The product of these quantities is often expressed in "ampere-turns".

For many years, the ampere-turn was used as the unit of magnetomotive force. However, as no additional base units are required to express the number of turns, this factor can be omitted without changing the dimension of the unit which is now the AMPERE.

4.5 **MAGNETISING FORCE.** Magnetising force is the term used to express the intensity of the magnetising field applied to a material. It depends upon the magnetomotive force and the length over which it is applied.

Magnetising force is therefore defined as the magnetomotive force per unit length. The symbol for magnetising force is H; the unit is the AMPERE PER METRE.

4.6 PERMEABILITY. We saw earlier that although all substances allow the passage of magnetic flux, the flux becomes more concentrated whenever it passes through magnetic materials. The degree to which a material concentrates magnetic flux is expressed as the permeability of the material.

The symbol for permeability is μ. Permeability is defined in two ways. These are:

- ABSOLUTE PERMEABILITY, which is the ratio of the flux density in a material to the magnetising force producing it.
- RELATIVE PERMEABILITY, which is the ratio of the flux density in a sample of the material to the flux density produced by the same magnetising force in an air gap having the same dimensions as the sample.

In engineering practice, relative permeability is the quantity most commonly used. It is expressed as a numerical ratio. As air is assumed to have a permeability of one, the value of permeability of a material is a direct indication of the ease with which it can be magnetised. For example, for a given magnetising force, the flux density in a sample of iron having a permeability of 4000, is five times as great as in an identical sample of hard steel having a permeability of 800.

For most magnetic materials, permeability is not constant, as it varies with different values of flux density in the material. For this reason, two permeability values are usually quoted when describing the properties of magnetic materials. These are:

- INITIAL PERMEABILITY, which is the permeability when the flux density approaches zero;
- MAXIMUM PERMEABILITY, which is the maximum value of permeability for the substance over a range of flux densities.

For example, the permeability of a typical grade of transformer iron is about 800 at very low flux densities. As the flux density is increased, the permeability increases till it reaches its maximum value of approximately 6000.

4.7 RELUCTANCE. Reluctance is analagous to resistance in an electrical conductor, in that it is the opposition offered by a material to the establishment of a magnetic flux. The reluctance of a material is directly proportional to its length, and inversely proportional to its permeability and cross-sectional area.

The symbol for reluctance is R. The unit of reluctance is the RECIPROCAL HENRY, which is written as 1/H or H^{-1}. (The henry is the unit of inductance, which is covered in another publication.)

4.8 THE MAGNETIC CIRCUIT. The factors which determine the intensity of the magnetic flux in a substance can be related in much the same way as those factors which determine the current in an electric circuit. For this reason, the complete path taken by magnetic flux is often referred to as the magnetic circuit.

In any magnetic circuit, the value of the flux depends upon the magnitude of the magnetomotive force and the value of the reluctance of the complete flux path.

Expressed mathematically,

$$\phi \propto \frac{F}{R}$$

where

ϕ = *Flux in webers;*

F = *Magnetomotive force in amperes;*

R = *Reluctance of the magnetic circuit in reciprocal henries.*

The relationship between the quantities in a magnetic circuit can be applied to derive the factors which determine the magnetic flux of a solenoid, such as that shown in Fig. 13. In this case, the solenoid is wound on an iron core containing an air gap, which forms part of the magnetic circuit.

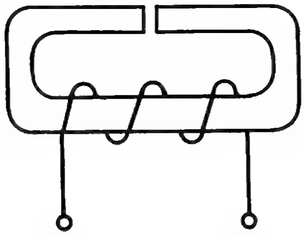


FIG. 13. MAGNETIC CIRCUIT OF A SOLENOID.

The magnetomotive force of the solenoid is determined by the value of the current in the winding and the number of turns it contains. In practice, the number of turns is generally fixed, and in most cases, there is no provision made to vary the value of the current, so that the value of the flux in the magnetic circuit is largely dependant upon its reluctance.

In the solenoid shown in Fig. 13, the total reluctance is the sum the individual reluctances of the iron and the air gap. As the permeability of iron is thousands of times greater than that of the air, the greater part of the total reluctance is due to the air gap, so that the length of the air gap has an important bearing on the value of flux.

In telecom equipment, there are many items which employ magnetic circuits containing an air gap. The satisfactory operation of these equipment items depends upon the attainment of a specified value of flux. As this depends to a great extend upon the dimensions of the air gap, the adjustment of this gap to the correct values is of major importance.

5. FERROMAGNETISM

5.1 For many years, it was believed that magnetic substances were composed of molecules which were tiny magnets. Upon the application of a magnetising force, it was thought that the molecular magnets came into line, and the substance as a whole exhibited magnetic properties.

The modern theory of magnetism explains magnetic behaviour as due to the electrons in the atoms which make up all matter. It is now generally accepted that electrons spin on their own axes as they orbit the nucleus. Just as the spinning earth has a magnetic field, it is assumed that all magnetic effects are due to spinning electrons.

5.2 **TYPES OF MAGNETISM.** In an atom containing many electrons, the spins of individual electrons may become oriented so that the atom as a whole, exhibits a magnetic field. Experiments have shown that most substances possess magnetic properties, although in many cases, the effect is very small. As the result of these experiments, it is possible to distinguish three classes of materials. These are:

- Diamagnetic materials, which tend to be repelled by magnetic fields;
- Paramagnetic materials, which tend to be attracted towards magnetic fields;
- Ferromagnetic materials, which like paramagnetics, are attracted by magnetic fields, but to a much greater extent.

While diamagnetism and paramagnetism are properties of individual atoms, ferromagnetism is a property of the crystal structure of ferromagnetic materials. From a practical viewpoint, all of the so-called magnetic materials are ferromagnetic, the most important of these being iron and its alloys, and to a lesser extent, nickel and cobalt.

5.3 FERROMAGNETIC DOMAINS. It has been found that in a crystal of a ferromagnetic material, such as iron, groups of atoms spontaneously align themselves so that the tiny magnetic fields of individual atoms are parallel. Within each group of atoms, the intensity of the magnetic field is at a maximum value, so that to a degree, each group of atoms resembles a small magnet.

Each group of aligned atoms is called a domain. Each domain contains some 10^{14} atoms, and there are about 10^5 domains in each of the 10^4 crystals in each cubic centimetre of iron.

In an unmagnetised piece of material, the domains are arranged in closed patterns so that the external magnetic effect is zero. Some simplified closed domain structures are shown in Fig. 14.

FIG. 14. TYPICAL DOMAIN STRUCTURES.

5.4 EASY DIRECTIONS OF MAGNETISATION. Experiments have shown that it is easier to magnetise a single crystal of iron in certain directions than it is in others. In iron, there are six easy directions, and in the unmagnetised state, the direction of the spontaneous magnetism of each of the domains in the crystal coincides with one of easy directions of magnetisation.

In its normal state, iron is polycrystalline, and unless specially treated, the crystal lattice is such that no single easy direction is continuous throughout a typical sample. When iron is magnetised, therefore, its magnetic properties depend to a large extent, upon the size of the crystals and upon their arrangement in the crystal lattice.

5.5 THE MAGNETISATION OF IRON. When a sample piece of iron is subjected to a magnetising force, the overall state of the magnetisation increases. There are two fundamental processes by means of which this occurs. These are:

- movement of the boundaries or walls of the domains;
- rotation of the axis of the spontaneous magnetisation within the domains.

The effects of these processes on the magnetisation of iron are shown on Fig. 15 in which the intensity of magnetisation or flux density (B), is plotted graphically against increases in magnetising force, (H). The resulting graph is called a B-H curve. The inset diagrams represent simplified changes in domain structure which occur at various stages of the magnetisation process.

With no magnetising force applied, the sample is unmagnetised as indicated by the closed domain structure shown in the lower inset diagram. The spontaneous magnetisation of the domains is shown along four of the easy directions, none of which corresponds exactly with the direction of the magnetising force.

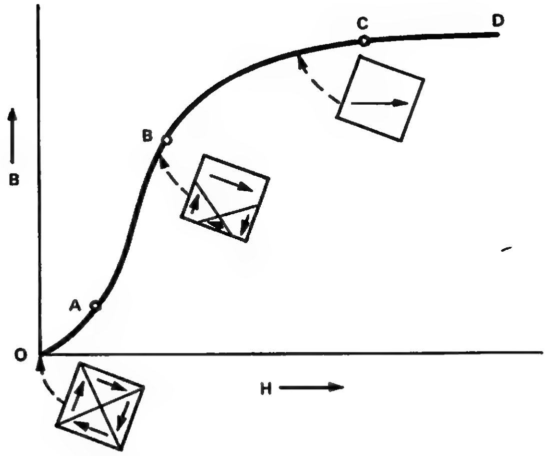


FIG. 15. TYPICAL B-H CURVE.

When a magnetising force is applied, the flux density increases slowly at first, because the domain boundaries are held in place by forces generated by stresses and imperfections within the crystal lattice. This process applies over section OA of the B-H curve, and the slope of this section is an indication of the initial permeability of the material.

As the magnetising force is increased further, the flux density increases rapidly as the domain boundaries begin to move. The movement is such that domains whose spontaneous magnetism most nearly correspond with the direction of the magnetising force become larger, while all others become smaller. This process is represented in the centre inset diagram and it continues till point B is reached on the curve. The maximum permeability value occurs within this region.

After the most favourably oriented domains have attained their maximum size, the flux density increases at a much slower rate, as the axis of the enlarged domains are rotated to line up with the direction of the magnetising force. This process accounts for the shape of the B-H curve from B to C.

When this reorientation is complete, as shown in the upper inset diagram, the magnetisation has attained its maximum value, and further increases in magnetising force cause no changes in flux density, as indicated in section CD of the curve. When all domains are in alignment with the direction of the magnetising force, the sample is said to be magnetically saturated.

Although the magnetisation process is represented by a smooth curve, in fact it proceeds in a series of small abrupt steps of jumps, too small to be represented on the B-H curve. It is also important to realise that the characteristics represented by the B-H curve shown in Fig. 15 are typical only, as the magnetic properties of iron can be changed significantly by adding selected impurities, or by mechanical processes such as heat treating and rolling.

5.6 MAGNETISATION CURVES.

The magnetic properties of a particular type of magnetic material are best demonstrated by subjecting a sample of the material to a complete cycle of magnetisation. This involves varying the magnitude and direction of the magnetising force so that the sample is saturated first in one direction, and then in the other.

When the resulting variations in flux density are plotted graphically for a complete cycle, the curve obtained has the form of a closed loop. The general shape of a typical magnetisation curve is shown in Fig. 16.

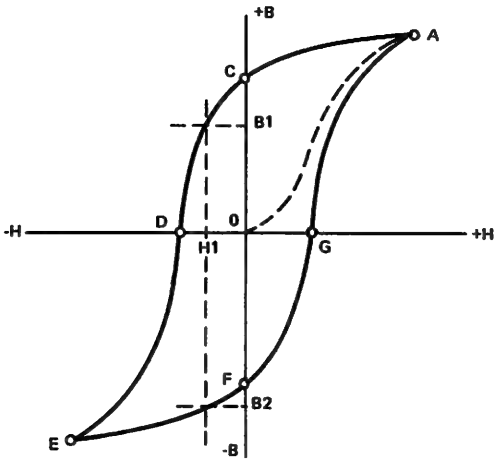


FIG. 16. TYPICAL MAGNETISATION CURVE.

The shape of the curve can be interpreted as follows:

- When the magnetising force is increased from zero to a value at which saturation occurs, the curve (OA) follows the form of the B-H curve for that particular material.
- As the magnetising force is decreased back to zero, the flux density decreases, but not at the rate at which it increased initially. When the magnetising force is zero there is a remanent value of flux density, represented on Fig. 16 by OC.
- The direction of the magnetising force is now reversed and its value is increased. The flux density decreases, and at a value of magnetising force represented on Fig. 16 by OD, it falls to zero. Further increases in magnetising force eventually cause saturation in the reverse direction at point E.
- The decrease in magnetising force to zero is again accompanied by a residual flux density (OF), which is neutralised by reversing the direction of the magnetising force and increasing it to a value represented by OG in Fig. 16.
- As the magnitude of the magnetising force is further increased, saturation is reached in the original direction to close the loop.

From the magnetising curve, two characteristic properties of a magnetic substance can be determined. These are:

- REMANENCE, which is the flux density remaining in the material after saturation, when the magnetising force has been reduced to zero. In Fig. 16, remanence is indicated by the dimension OC or OF.
- COERCIVE FORCE, which is the magnetising force required to reduce the remanent flux density to zero. In Fig. 16, coercive force is indicated by the dimension OD or OG.

Inspection of the magnetisation curve also shows that the degree of magnetisation of a ferromagnetic substance, depends not only on the applied magnetising force, but also upon its previous magnetic state. In Fig. 16, for example, the flux density resulting from the application of a magnetising force of H1, could have either of two values, B1 or B2, depending upon the direction in which the material was magnetised previously.

5.7 HYSTERESIS. The lag in changes of flux density behind the changes in magnetising force is termed *hysteresis* and the complete magnetisation curve is known as a hysteresis cycle or hysteresis loop. The phenomenon of hysteresis is not restricted to ferromagnetic materials, as it is exhibited by any substance or device in which remanent effects are evident. In magnetism, hysteresis can be explained in terms of movement of demain boundaries.

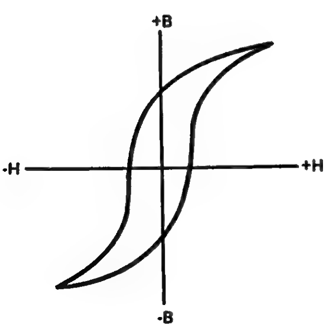
In the paragraph dealing with the shape of the B-H curves, we saw that the initial movement of domain boundaries is impeded by imperfections in the crystal lattice caused by mechanical stresses, or by impurities in the material. When a magnetising force is first applied, these imperfections tend to tether the domain boundaries until the force has been increased sufficiently to allow the boundaries to break away. At this point the domain boundaries move freely and the flux density increases, until the boundaries are stopped by other imperfections.

If the magnetising force is now removed, there is no tendency for the boundaries to return to their original positions, as the forces which prevent their further movement in the presence of a magnetising force effectively retain them in this position when the force is removed. To restore the material to the unmagnetised state, it is necessary to apply a magnetising force in the reverse direction, so that the domain boundaries can break away from the imperfections in the lattice and spring back to their original positions.

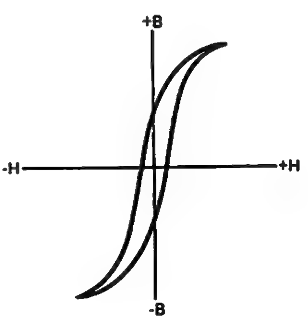
In a ferromagnetic material, therefore, the factors which determine the initial permeability also effect the coercive force, and any process which increases the value of one usually decreases the value of the other. This characteristic is noticeable in most magnetic materials, and generally those alloys which are notable for their high values of initial permeability usually have corresponding low values of coercive force. In the same way a material which features high coercive force, usually has a fairly low value of initial permeability.

5.8 HYSTERESIS LOSS. When ferromagnetic material is subjected to a continually reversing magnetising force, energy is expended in overcoming the forces which tend to tether the domain boundaries. This energy appears as heat in the material, and is therefore considered an energy loss. This loss is called hysteresis loss.

Hysteresis loss varies in value from one material to another, and generally, the area enclosed by the hysteresis loop of a substance can be regarded as an indication of its hysteresis loss. For example, the material represented by the loop shown in Fig. 17a will incur a greater energy loss than will the material represented by Fig. 17b, when both are operated under similar conditions.



(a) Large Loss.



(b) Small Loss.

FIG. 17. HYSTERESIS LOOPS.

The amount of energy lost during each magnetisation cycle is generally quite small, and it has been calculated that an ordinary piece of iron would need to be taken through about 4,000 complete magnetisation cycles to raise its temperature by 1°C. However, some items of telecom power plant, such as large transformers, contain iron cores which are driven through 50 complete magnetisation cycles each second, and as these usually operate continuously, it is important that the iron used has very low hysteresis loss.

5.9 MAGNETOSTRICTION. Magnetostriction is an effect whereby a material undergoes a slight change in length when it is magnetised. The extent of the change varies from one material to another, and, depending upon the nature of the material, it may be either an expansion or a contraction.

This effect is noticeable in all ferromagnetic materials, although it is most pronounced in nickel. Magnetostriction has only limited application in telecom equipment, but it is used extensively in the generation of ultrasonic waves.

6. MAGNETIC MATERIALS.

6.1 Magnetism plays an important part in the operation of telecom equipment, and because of its wide field of application, many types of materials with a variety of different characteristics are used. Generally, magnetic materials can be broadly divided into two groups, which are referred to as "soft" and "hard" magnetic materials respectively.

6.2 SOFT MAGNETIC MATERIALS. Soft magnetic materials are those which can be magnetised and demagnetised comparatively easily. They are commonly used where the magnetisation is of a temporary nature, for example, as in some electromagnets, or where it is required to provide a low reluctance path for magnetic flux.

The desirable characteristics of a soft magnetic material are:

- high permeability, that is, high values of flux density can be obtained with comparatively small values of magnetising force;
- low coercivity, that is, only small values of coercive force are required to remove the remanent flux density after magnetisation.

The most commonly used soft magnetic material is iron, typical characteristics of which are shown in Fig. 18a. Special iron alloys which are used in telecom include Stalloy (iron, silicon and aluminium), Permandur (iron,cobalt and vanadium) and Permalloy (iron and nickel).

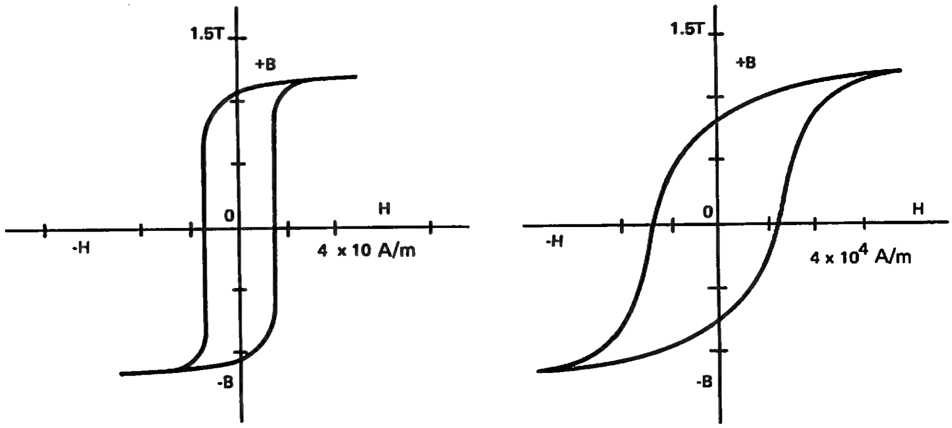
A feature of these alloys is their high initial permeability, which is important in telecom applications where the magnetising forces can be very small. In this regard, some types of nickel-iron alloys have initial permeability values of about one thousand times greater than that of ordinary soft iron.

6.3 HARD MAGNETIC MATERIALS. Hard magnetic materials are used for permanent magnets, whose function it is to establish and maintain a magnetic flux in a magnetic circuit. Generally, these materials must be capable of retaining a constant magnetomotive force indefinitely, and be able to withstand the demagnetising effects of mechanical shock, vibration and stray magnetic fields.

The essential magnetic characteristics of hard magnetic materials are:

- high coercivity, so that the magnet does not demagnetise;
- high remanent flux density so that the desired field strength can be obtained.

Until the mid-1930s, the most commonly used hard magnetic materials were steels containing a percentage of tungsten or cobalt. However, discoveries made about this time led to the development of new alloys such as "alnico" (aluminium, nickel, iron and cobalt) which have extremely high coercivity, and do not exhibit the ageing characteristics of earlier materials. The characteristics of alnico are shown in Fig. 18b. When comparing these with the characteristics of soft iron, it is important to note the different scales used for magnetising force.



(a) Soft Iron. (b) Alnico.

FIG. 18. COMPARISON OF MAGNETIC CHARACTERISTICS.

6.4 FERRITES. In addition to the ferromagnetic metals and their alloys, there exists a group of substances which exhibit strong ferromagnetic properties, but which, strictly speaking, cannot be classed as ferromagnetic. These substances, called ferrites, are not metals, but are mixtures of oxides of iron with other metal oxides. The earliest known magnetic material, "lodestone," (Fe_3O_4) actually belongs to this group of substances.

Ferrites are made by mixing the various oxides together in the correct proportions, and by heating the mixture to a high temperature, usually between 1200°C and 1350°C, for several hours. The resulting substances are usually black in colour, extremely hard and very brittle. They are made in a wide variety of shapes and sizes, and different types of material are available to suit either hard or soft magnetic applications.

Generally, magnetically soft ferrites have initial permeability values which approach those of nickel-iron alloys, and the magnetically hard ferrites, have coercive force values higher than those attained in alnico type alloys. All types of ferrites however, are electrical non-conductors, and it is this feature which makes them so useful in telecom equipment.

Whenever conducting magnetic materials such as iron are used in the cores of devices which operate with rapidly changing magnetic fields, electric currents called eddy currents are induced in the iron. These eddy currents are detrimental to the operation of iron cored devices at high frequencies in two ways. These are:

- The efficiency is reduced. Eddy currents cause an energy loss which increases as the frequency of operation increases. At very high frequencies, the energy losses are so great that iron cored devices are unworkable.

- The permeability of the iron core is effectively reduced. Eddy currents confine the magnetisation to a thin layer near the surface of the material. As the frequency of operation becomes greater, the depth of the magnetised layer becomes less, so that at very high frequencies, the presence of an iron core has little or no effect on the flux density attained.

As ferrites are nonconductors, eddy currents and their effects do not occur. Ferrites, therefore can be used in magnetic circuits in which the intensity and direction of magnetisation changes very rapidly, and as such have a wide field of application in telecom equipment.

6.5 SQUARE-LOOP MATERIALS. A group of magnetic materials which is becoming increasingly important in telecom equipment consists of those substances possessing the "square-loop" characteristic. This term refers to the shape of the hysteresis loop of the material which is similar to that shown in Fig. 19.

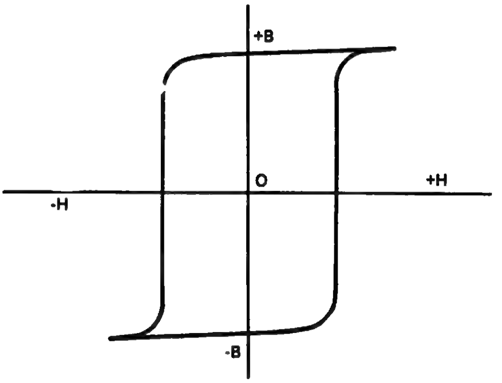


FIG. 19. SQUARE HYSTERESIS LOOP.

The squareness of the hysteresis loop is due to the special magnetic properties of these materials, which include:

- very high permeability with a high value of flux density at saturation;
- very high remanence, not significantly less than the flux density at saturation;
- a high value of coercive force which is the same for all domains in the material, so that the value of magnetising force at which demagnetisation takes place is sharply defined.

A typical square-loop material is HCR alloy (50% iron, 50% nickel) which is frequently used as core material in the control devices of some types of automatically regulated power plant. Square-loop ferrites are also available, and these are used in the "memory" section of some types of computers.

7. INDUCED E.M.F's AND CURRENTS

7.1 Faraday's experiments investigating the relationship between electricity and magnetism, resulted in the formulation of his law of electromagnetic induction, which can be stated as follows -

When relative motion exists between a magnetic field and a conductor, an e.m.f. is induced in the conductor, and when the circuit is closed a current flows.

For example, Fig. 20 shows a coil of wire wound on a circular former; the ends of the coil are connected to a sensitive centre zero electrical instrument. When the north pole of a bar magnet is inserted into the middle of the tube, the instrument needle is immediately deflected to one side, and then returns to zero. When the magnet is withdrawn, the needle is again deflected, but in the opposite direction, and again returns to zero.

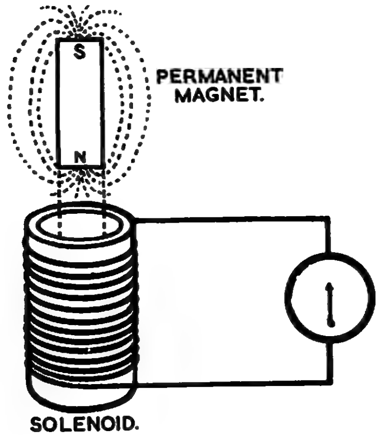


FIG. 20. RELATIVE MOVEMENT INDUCES AN ELECTRIC CURRENT.

When the South pole is inserted, a momentary deflection of the needle occurs in the same direction as when the North pole is withdrawn. Conversely when the North pole is inserted, a deflection occurs in the same direction as when the South pole is withdrawn.

When the coil is moved, and the magnet is stationary, these same induced effects occur. There is, therefore, a relationship between the relative movement and the direction of the resultant e.m.f. and current, as we shall see later.

The principle of this action, which is the basis of Faraday's Law, is that the magnetic field moves with the magnet, and when the magnet is inserted into the coil, the lines of force comprising the magnet's field *link* or *cut* the turns of the coil. This *cutting* sets up an induced e.m.f. across the coil, and a resultant current passes through the completed circuit of coil and meter.

The current only occurs when the magnet or coil is in motion; as soon as the magnet or coil comes to rest, the current stops.

The value of induced e.m.f. and resultant current flow is dependent upon:

- the field strength of the magnet; the stronger the field, the greater is the induced effect;
- the number of turns on the coil; an increase in turns increases the induced effect;
- the speed of *cutting*; the faster the relative motion, the greater is the induced effect.

Remember, the induced effect is only transient; *it lasts only while the magnet or coil moves.*

7.2 When an energised electromagnet is substituted for the permanent magnet, as shown in Fig. 21, similar results are obtained.

Further, when the electromagnet is placed in the coil and a means (for example, a switch) provided to stop and start the current through the electromagnet, a current is induced in the coil without movement of the electromagnet.

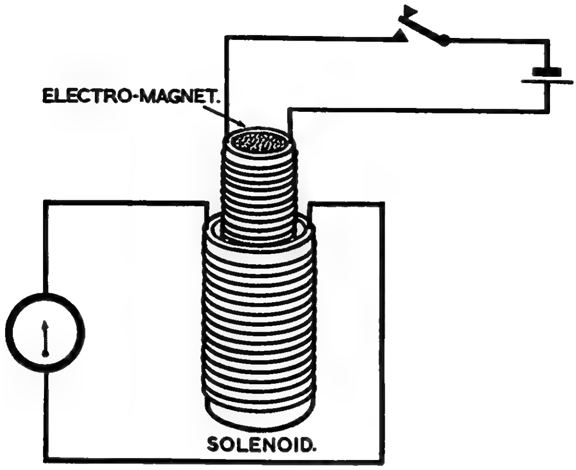


FIG. 21. ANOTHER METHOD OF INDUCING AN ELECTRIC CURRENT.

The closing of the circuit of the electromagnet allows current to flow. This current creates a magnetic field, and as the lines of force are established and expand, they cut the turns of the coil. When the circuit of the electromagnet is opened, the field collapses and the lines of force cut across the turns of the coil in the opposite direction.

As we shall see later, such an apparatus is an *induction coil* or *transformer*, the coil of the electromagnet acting as the *primary* circuit and the outer coil as the *secondary* circuit.

7.3 We can summarise these effects in the following way.

An induced e.m.f. will occur when:

- relative motion occurs between a magnet and a coil;
- relative motion occurs between an energised electromagnet and a coil;
- the current in an electromagnet is stopped, started or varied.

The magnitude of the induced effect varies as the strength of the magnetic field, and the rate of movement.

These principles are the basis of electromagnetic induction, and experiments prove that there are definite relationships between the factors producing it.

7.4 **RIGHT HAND RULE.** We found in para. 7.1 that there is a definite relationship between the direction of motion, direction of magnetic field, and the direction of the induced current. This can be determined by the right hand rule for generators (Fig. 22).

When the thumb, first, and second fingers of the right hand are held at right angles to each other like the three boundaries at the corner of a cube, with the first finger pointing in the direction of the field (N to S), the thumb pointing in the direction of motion, then the second finger indicates the direction of the resulting e.m.f. and current.

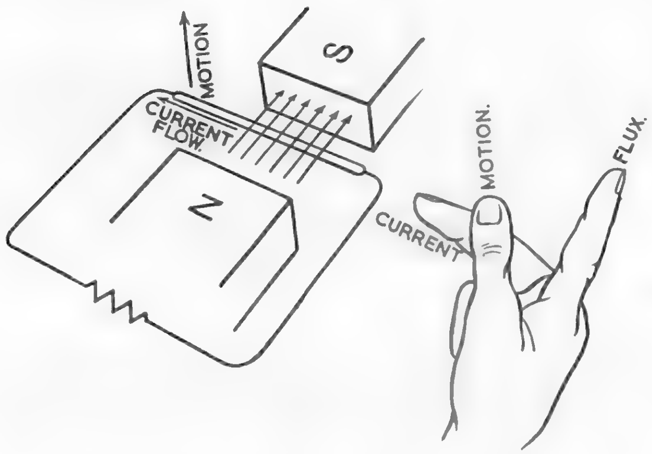


FIG. 22. RIGHT HAND RULE FOR GENERATORS.

7.5 Maximum e.m.f. and current are induced when the direction of motion, and the field, are at right angles. Variations from a right angle between the two, produces a variation in the rate of cutting, and consequently in the magnitude of the induced effect, from maximum at right angles, to zero when the field and motion are parallel.

Although it is customary through common usage to speak of induced currents, it is important to remember that it is the e.m.f. that is induced; a current flow will result if the circuit conditions are suitable.

7.6 LENZ'S LAW. We have seen that relative motion between lines of force and a conductor produces an induced e.m.f., and if the circuit is closed, a current. However, an examination of the following conditions shows that the magnetic effect of the induced current tends to oppose the originating motion.

With the conductor at rest, there is no induced effect, and no magnetic field around the wire, the only field present being due to the permanent magnet (Fig. 23a).

When the wire is moved downwards into the permanent magnet's field, an e.m.f. is induced, and the flux produced by the resultant current, combines with the magnet's field to produce a magnetic effect which opposes the motion of the conductor into the field (Fig. 23b).

From similar experiments, Lenz, a Russian physicist, formulated his law, which is expressed as follows.

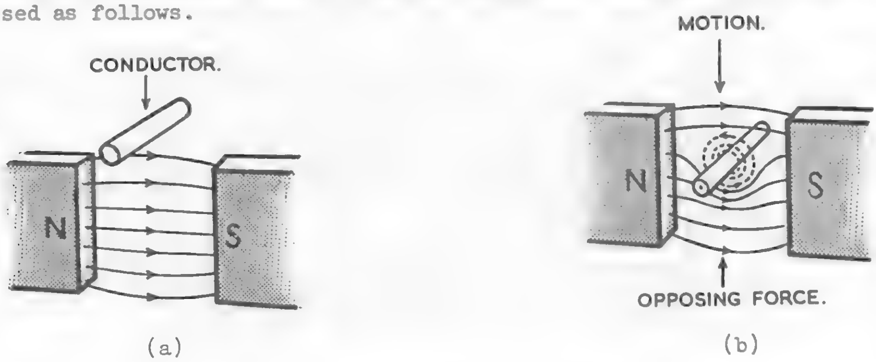


FIG. 23. PRINCIPLE OF LENZ'S LAW.

Induced currents (and e.m.f's) are always in such a direction, that their effects tend to oppose the motion which produces them.

An electric current possesses energy, and a current can only appear through the expenditure of some form of energy, which is in this case mechanical. From this it follows that the greater the induced current, the greater will be the opposition to its creation, and the greater will be the expenditure of energy necessary to produce it.

Both Lenz's and Faraday's Laws are important in telecommunication theory, and have a wide application in all forms of electrical apparatus.

8. GENERATORS

8.1 A.C. GENERATOR. This generator sometimes called an alternator, uses the principle of induction, and a coil of wire is mechanically rotated in the field produced by a permanent magnet or electromagnet. As the coil rotates, it cuts the magnetic field and an alternating voltage is induced across the coil. When the coil is connected to a closed circuit, current flows.

8.2 Fig. 24 shows how this current is generated by the rotation of a single turn of wire ABCD in a magnetic field, with connection made from the coil to the external load by slip rings and brushes. An application of the right hand rule shows the direction of current flow at the various positions of the coil of wire.

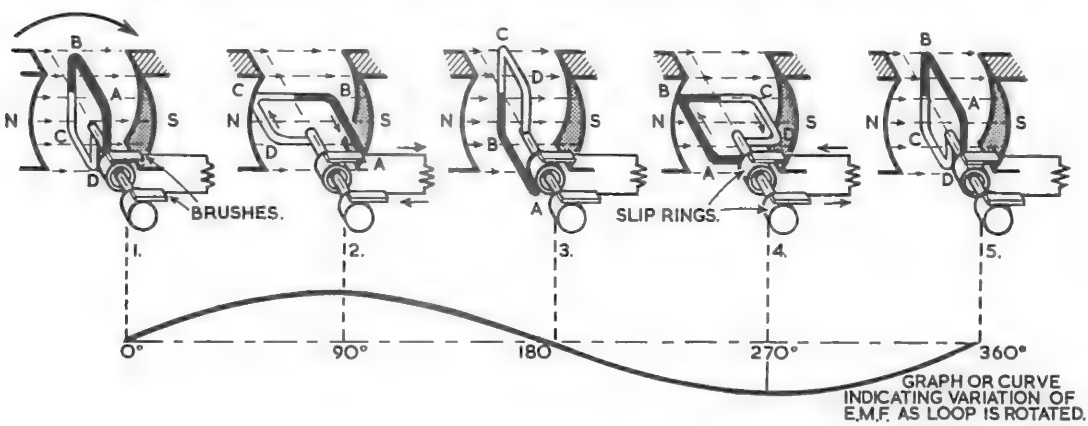


FIG. 24. HOW THE GENERATOR GENERATES A CURRENT.

In position 1, both sides of the turn are moving parallel with the lines of force and, therefore, do not cut the field. In this position there is no induced e.m.f.

At 2, side A-B of the turn is moving downwards and the side C-D is moving upwards, and both sides are cutting the field at right-angles. E.M.F's in series are induced across the two sides of the turn, as shown in Fig. 24, so that the current in the external circuit is in the direction A to D. As the turn moves from 1 to 2, the voltage increases gradually from zero in 1 to a maximum. This is because the sides of the turn cut a gradually increasing number of lines per unit time as the turn rotates from position 1 to position 2.

At 3, the induced e.m.f. is again at zero, and, at 4, is a maximum in the D to A direction in the external circuit. This is because in position 4, side A-B is now moving upwards across the field and side C-D is moving downwards.

Included in Fig. 24 is a graph of the variation in the value and direction of the induced e.m.f., and, therefore, the voltage applied across the external circuit for one revolution of the coil turn. From this graph, it is seen that the e.m.f. generated across the turn is alternating, one complete cycle being generated for each revolution of the armature.

8.3 In practice, the single loop of wire shown in the diagram is replaced by a coil of many turns of insulated wire, wound upon a soft iron core, called an *armature*, which is turned by a handle or a motor.

E.M.F's are generated in each turn of the coil, and so the total e.m.f. produced by the generator is increased in direct proportion to the number of turns. Thus, for the same speed of rotation, a generator with a coil of ten turns generates ten times the e.m.f. of a similar machine with only a single loop.

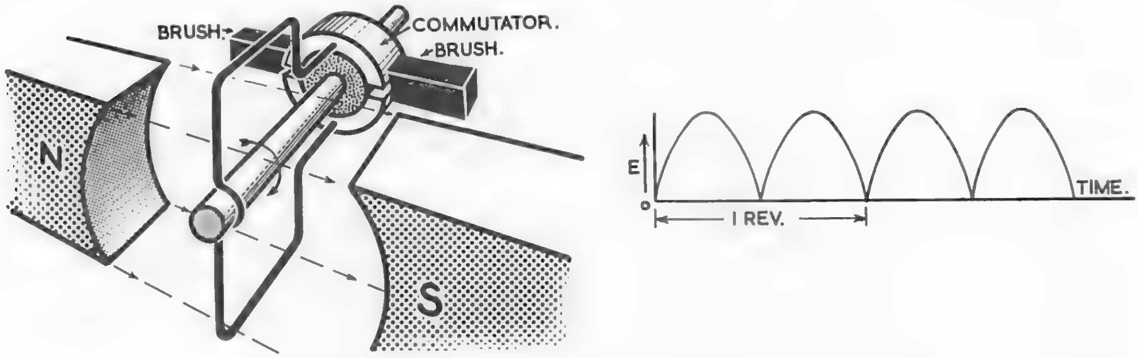
The iron core increases the induced e.m.f. by increasing the intensity of the magnetic field in which the coil rotates.

8.4 DIRECT CURRENT GENERATOR. The D.C. generator is the same in principle as the A.C. generator, but uses a device called a commutator to convert the induced A.C. of the armature so that a D.C. flows in the external circuit. The machine consists of conductors rotating in a magnetic field, but the coil, instead of being connected to *slip rings* as in an alternator, is joined to the two halves of a *split ring* which is mounted on, but insulated from the generator shaft (Fig. 25a).

The split ring is termed a *commutator*, and acts as an automatic reversing switch which reverses the coil's connections to the external circuit each time the coil current reverses.

The current pick-up and connection to the external circuit is made by brushes, usually of carbon, which are mounted in such a position to the magnetic field, that the connection changes from one commutator segment to the other when the coil current is zero.

The output from this type of generator is unidirectional, but pulsating (Fig. 25b), the speed of pulsations being determined by the speed of the generator.



(a) (b)

FIG. 25. SIMPLE COMMUTATION

8.5 Commercial machines have a number of coils spaced around the armature with a correspondingly larger number of commutator segments, each of which is a junction point for the connection of two coils. In this way, fluctuations of output are reduced and a practically steady D.C. is obtained.

8.6 In both A.C. and D.C. generators, when a load is connected across the output terminals, the resultant current through the armature produces a field which, by Lenz's law, interacts with the generator's field in such a direction as to oppose the rotation of the armature which is producing it.

As a result, the larger the electrical load, and the heavier the output current, the greater will be the mechanical force required to turn the generator.

8.7 **TYPES OF GENERATORS.** In telephone instrument generators, the magnetic field is provided by a permanent magnet, but most practical generators have electromagnetic fields. To produce a constant field, the field coils must be connected across a D.C. supply. (A.C. does not produce a constant polarity and is therefore not suitable.)

The current in the field coils is called the *excitation current*, and may be supplied from a separate D.C. source or by using the D.C. output of the generator itself.

Generators are classified according to the way in which the fields are excited, and these are:

- separately excited generators;
- self excited generators.

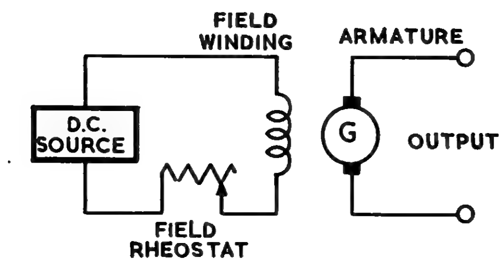


FIG. 26. SEPARATELY EXCITED GENERATOR.

8.8 **SEPARATELY EXCITED GENERATOR.** When the field coils of the generator are energised from a separate D.C. source, such as cells or another D.C. generator, it is said to be *separately excited* (Fig. 26).

This type of generator has two independant circuits. One is the field coils and separate D.C. source, and the other is the armature and load resistance. A variable resistance, called the *field rheostat,* is generally provided to vary the excitation and the output of the machine.

8.9 **SELF EXCITED GENERATORS.** When some of the generator output is used for field excitation, the generator is *self excited,* and the residual magnetism in the pole pieces is depended upon to provide the initial field for the armature windings to cut. When the induced e.m.f. produces a small current in the armature, portion (or the whole) of the output D.C. passes through the field and builds up the magnetic flux, increasing the generated e.m.f.

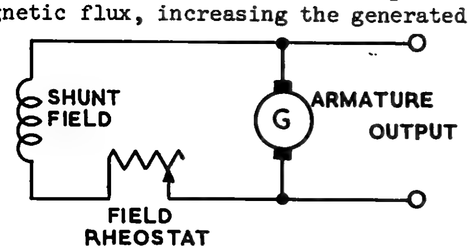


FIG. 27. SHUNT FIELD.

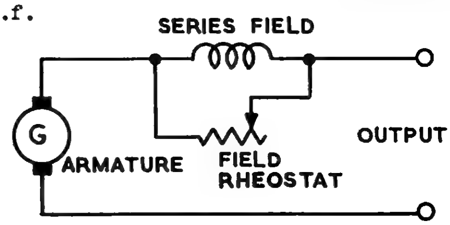


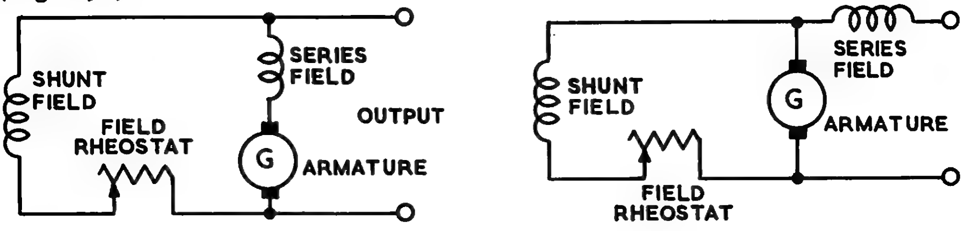
FIG. 28. SERIES FIELD.

Self excited generators are classified according to the type of field connection used; these are:

- SHUNT FIELD GENERATOR. During rotation under load, the armature current divides between the load and field (Fig. 27). The field which is in parallel with the armature is generally of high resistance, and only a fraction of the output current passes through it.

- SERIES FIELD GENERATOR. The field is connected in series with the armature and load (Fig. 28). With the machine on load all of the output current passes through the field, and the field must be of sufficiently heavy gauge of conductor to carry the full output current without overheating.

- COMPOUND FIELD GENERATOR. This is a combination of shunt and series windings designed to combine the advantages of both types. There are two methods of field connections, the *long shunt* field, where the shunt field is connected across the series field and the armature (Fig. 29a), and the *short shunt* field, where the shunt field is connected across the armature only (Fig. 29b).



(a) Long Shunt. (b) Short Shunt.

FIG. 29. COMPOUND FIELD.

Field rheostats are usually used to control the output of the machine by varying the field current.

8.10 The performance of a generator (or motor) depends upon its field characteristics and connections, and each type has its own particular characteristics and applications. These are dealt with in other papers of the Course.

9. MOTORS

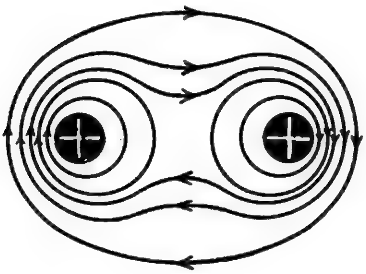
9.1 MECHANICAL FORCE EXERTED ON A CONDUCTOR IN A MAGNETIC FIELD.

We saw earlier that the direction of a magnetic field can be mapped by utilising the mechanical force that it exerts on a compass needle, in turning it in a direction at right angles to the field.

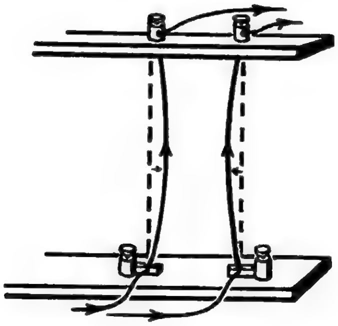
Since the direction of any magnetic field can be found in this way, we can determine the effects of magnetic fields on one another, by using the two fundamental laws of attraction and repulsion of magnetised bodies.

When two conductors are placed side by side, and are carrying a current in the same direction, the magnetic fields are in the same direction, and combine, forming a stronger magnetic field (Fig. 30a). Since lines of force tend to shorten, there is a force of attraction between the two conductors.

This is demonstrated by the simple experiment shown in Fig. 30b. The two long flexible conductors suspended at both ends, and parallel to each other, have currents in the same direction through them. The combination of the two fields produces a force of attraction, and the two wires bend towards each other.



(a)

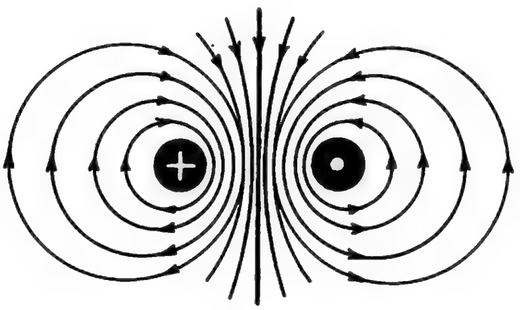


(b)

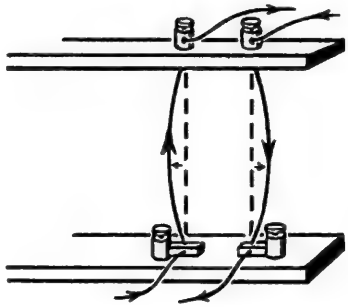
FIG. 30. SIMILAR DIRECTION OF CURRENT THROUGH PARALLEL CONDUCTORS.

When the current is in opposition through the conductors, the magnetic fields oppose one another, (Fig. 31a,) and since the lines of force will not cross, there is a force of repulsion between the conductors (Fig. 31b).

Again, this effect is demonstrated by the two parallel conductors (Fig. 31b). When current flows through the conductors in opposite directions, the repulsion between the two fields forces the conductors apart.



(a)



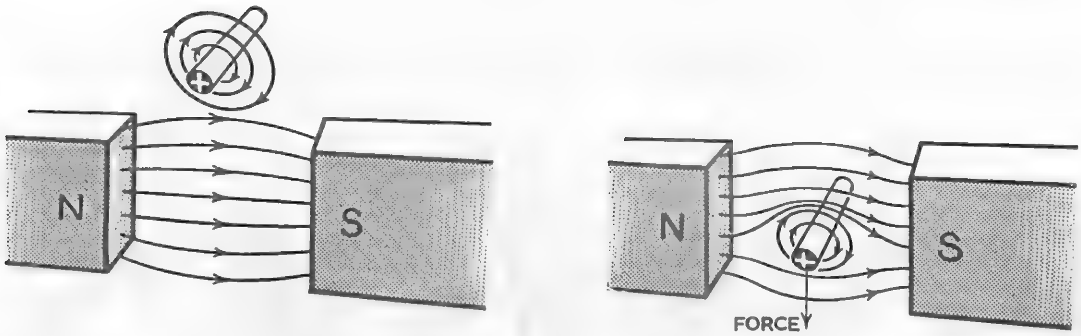
(b)

FIG. 31. OPPOSITE DIRECTION OF CURRENT THROUGH PARALLEL CONDUCTORS.

SUMMARISING. Parallel conductors, each carrying a current, experience mutual forces of attraction or repulsion depending upon whether the currents are in the same or opposite directions through them.

9.2 The same repulsion and attraction between combining fields is produced when a current-carrying conductor is placed between the poles of a permanent magnet.

The two fields, one due to the magnet, and the other due to the current in the conductor, are shown in Fig. 32a. When the conductor is placed in the magnet's field, the combination of the two fields strengthens the field above, and weakens the field below the conductor, with the result that a force is exerted on the conductor, tending to move it downwards (Fig. 32b).



(a) (b)

FIG. 32. MOTOR PRINCIPLE.

When the direction of current is reversed, (or the magnet polarity is reversed), the two fields combine to produce a force tending to move the conductor upwards.

The development of a force on a current-carrying conductor in a magnetic field is termed the *motor principle,* as an electric motor depends for its operation on a force developed in this way.

9.3 LEFT HAND RULE FOR MOTORS. This relationship between the direction of current, direction of the magnetic field, and the resultant movement of the conductor is determined by the left hand rule (Fig. 33).

When the thumb, first, and second fingers of the left hand are held at right angles to each other, like the three boundaries at the corner of a cube, with the first finger pointing in the direction of the field (N to S), and the second finger pointing in the direction of current, then the thumb indicates the direction of movement of the conductor.

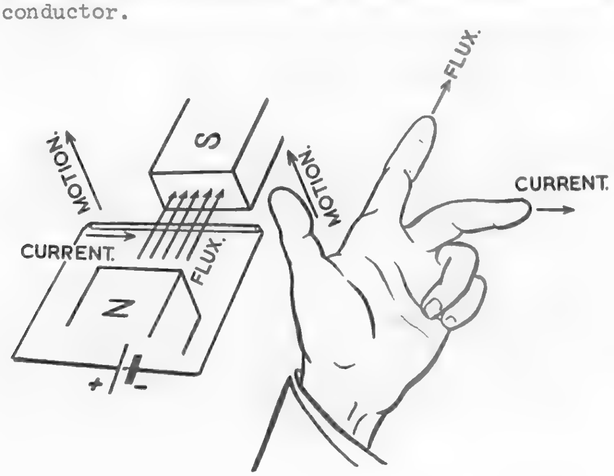


FIG. 33. LEFT HAND RULE FOR MOTORS.

9.4 SIMPLE MOTOR. Let us consider a coil AB which is pivoted and free to rotate between the poles of a permanent magnet (Fig. 34a).

The ends of the coil are connected to a two segment commutator, and mounted in such a way that when the coil is vertical the brushes are at the point of changing from one segment to the other (Fig. 34b).

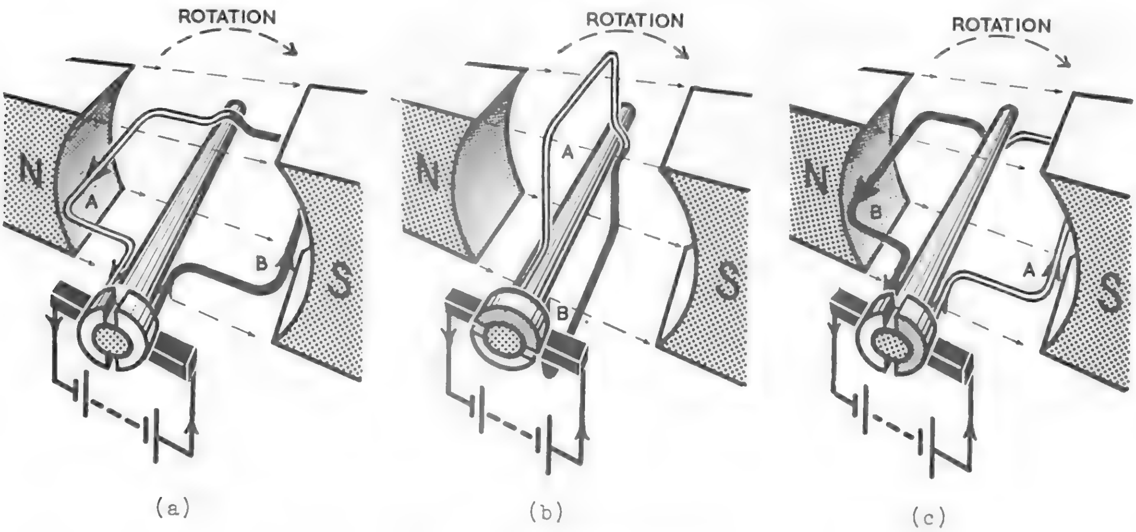


FIG. 34. THE SIMPLE MOTOR.

When a battery is connected to the brushes and current flows from B to A, the interaction between the coil conductor's field and the magnet's field causes rotation of the coil (Fig. 34a). When the coil reaches the vertical position, the current is zero for an instant (Fig. 34b), and then reverses in direction from A to B as the connections to the battery have been reversed by the commutator.

The force on the coil conductors is thus reversed and the coil continues to rotate in the same direction (Fig. 34c). In this way, continuous rotation is obtained by the conversion of electrical energy into mechanical energy.

9.5 FIELD EXCITATION. In practice, the main magnetic field is provided by electromagnets which have as a core the shaped pole pieces. The method of connection of field and armature can be either series, shunt, or compound. Each of these types of motors has different performance characteristics for different applications in industry.

9.6 ARMATURE BACK E.M.F. When the armature conductors are moving, there is an e.m.f. induced in them, which by Lenz's law is in opposition to the applied e.m.f. and current. Providing the field strength remains constant, this back e.m.f. increases with speed, and the motor will reach a speed where the applied e.m.f. and back e.m.f. are almost equal, and the motor settles down at that speed; sufficient current is drawn from the source to maintain the motor's speed against the opposition of friction.

When a mechanical load is placed on the motor, the speed of the armature in cutting the field decreases, and the value of back e.m.f. decreases. As a result a greater current flows in the motor circuit, providing a greater expenditure of electrical energy to overcome the increased mechanical load.

10. INDUCTION AND INDUCTANCE

10.1 MUTUAL INDUCTION. We saw in Section 7 that when an electromagnet is placed within a coil, and the current through it changed, an e.m.f. is induced in the coil without movement of the electromagnet.

When a current changing in one circuit, induces an e.m.f. in a neighbouring circuit, the effect is known as *mutual induction*, and it is upon this principle that the transformer operates.

10.2 Let us now re-examine the laws of Faraday and Lenz in their application to the transformer, where the relative motion between the two bodies is that of the moving field, and not a physical movement of either body.

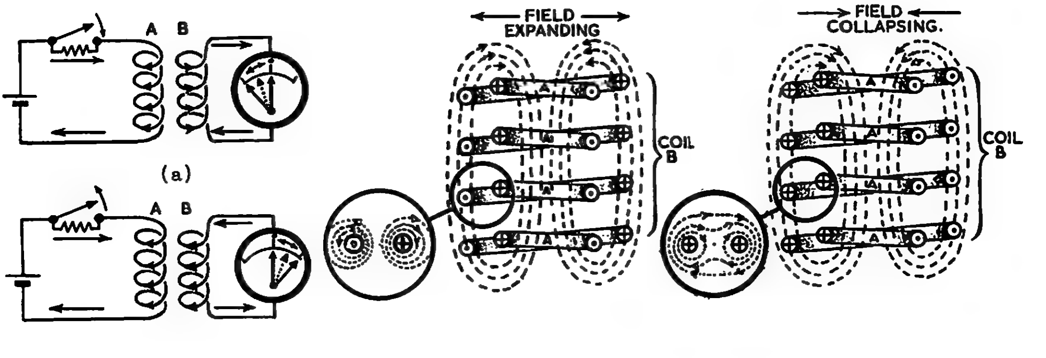


FIG. 35. INDUCING A CURRENT.

Two coils A and B are connected as shown in Fig. 35. When the switch is closed the current increases as the resistor across the switch contacts is short circuited. As a consequence, the existing magnetic field around coil A increases, and in expanding, cuts coil B. By Faraday's Law this relative motion results in an induced e.m.f. and current whilst the flux is changing, and a momentary reading on the meter. (Fig. 35a).

When the switch is opened, the inserted resistance reduces the value of current in A. The magnetic field in collapsing to its new value cuts coil B and induces a transient current in the opposite direction to the first induced effect. Once again the transient current indicated by the meter lasts only while the flux is changing.

As it is the *change* in flux which produces the induced effect, the same results are achieved when a pulsating D.C. or an A.C. is applied to coil A, instead of the varying D.C. shown.

The principle outlined in Figs. 35a and 35b has its application in the operation of a telephone's speaking circuit.

10.3 The application of Lenz's Law in this example can be seen in Figs. 35c and 35d, which show the coils wound one on the other. The application of the appropriate rules shows that when coil A's current increases, the magnetic flux resulting from the induced current in coil B is in an opposing direction to the flux of coil A. Also when coil A's current decreases, the direction of induced current is such that its flux tends to maintain the originating flux of coil A, again *opposing the motion that creates it.*

In the application of the rule of *relative motion*, remember that the motion of the field and conductor is relative, and the thumb, will be applied in the rule as though the conductor and not the field is moving.

10.4 SUMMARY. Any variation in flux linkage caused by a changing current of either D.C. or A.C. in one coil, will cause an induced e.m.f. in a coil with which it is magnetically linked; the magnetic effect of any induced current is in such a direction as to oppose the change of current which is producing it.

10.5 SELF INDUCTANCE AND INDUCTANCE. We have considered the induced effect produced by one coil on another; now let us examine the induced effects produced in a circuit consisting of a single coil.

When a source of e.m.f. is applied to a coil, and current flows in the coil, the resulting magnetic flux rises and links the turns of the coil, inducing across its turns an e.m.f. which, by Lenz's law, will be in opposition to the applied e.m.f. When the current reaches the Ohm's law value, the flux becomes stationary and the induced effect disappears.

This effect of a current, changing in a coil or conductor, and inducing an e.m.f. in reverse to that applied, is termed *self induction*. The induced e.m.f. is sometimes termed the *back e.m.f.*, and as a result, the current rise from zero to the final steady value takes a certain time in this type of circuit.

When the current in the circuit is increased, more lines of force are established, and the e.m.f. of self induction opposes the current rise. When the current ceases or is decreased, the flux linkages are decreased, and the e.m.f. of self induction is in such a direction as to maintain the current, or oppose its fall.

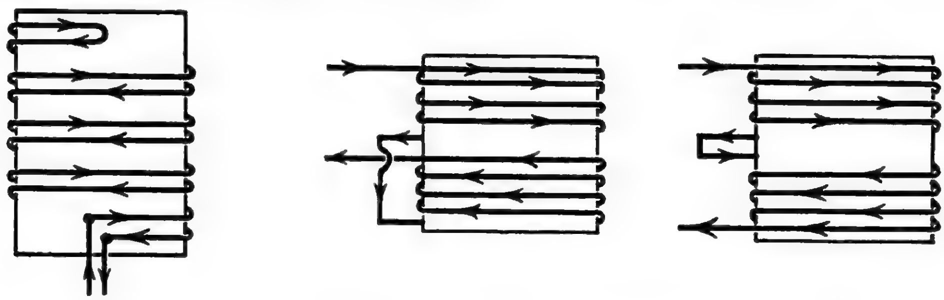
In this latter case, when the circuit is opened, the dissipation of the electrical energy produced by induction can be observed, as the self induced e.m.f. produces a spark across the switch contacts when they open.

10.6 The *property* of any electric circuit, by which a voltage is induced in the circuit when the current is started, stopped or changed in value is called *inductance*.

A circuit possesses the property of *self inductance* when a current changing in the circuit, induces an e.m.f. in the same circuit.

A circuit possesses the property of *mutual inductance* when a current changing in the circuit, induces an e.m.f. in a neighbouring circuit.

10.7 UNIT OF INDUCTANCE. The unit of inductance is the Henry, and a circuit has an inductance of 1 Henry when a current with a rate of change of one ampere per second induces in it an e.m.f. of one volt.



(a) (b)

FIG. 36. NON-INDUCTIVE RESISTANCES.

10.8 NON–INDUCTIVE RESISTANCE (N.I.R.). In some types of apparatus, it is necessary to introduce a resistance coil possessing negligible inductance. Such a winding is termed a *non-inductive resistance*. The self inductance of a wire can be neutralised by doubling the wire back on itself and winding from the centre of the length of wire (Fig. 36a). The magnetic effect of the current in one direction through the winding is equal and opposite to that produced by the same current in the opposite direction, resulting in a non-inductive winding.

Another method used when the length of wire is inconveniently long is to wind the wire in the form of two separate equal coils, connecting the windings so that the magnetic effect of one is neutralised by the magnetic effector of the other (Fig. 36b).

10.9 INDUCTIVE REACTANCE. Since any change in current value through a coil produces an e.m.f. in opposition to the applied e.m.f., this opposition reduces the effect of the applied e.m.f. in producing a current through the coil.

Also, the magnitude of induced e.m.f. depends on the rate of change; therefore, the faster the rate of change, the greater the magnitude of the induced e.m.f., and the slower will be the rise of current in the coil to the final value.

This opposition to the current, caused by the self induced or back e.m.f. in an A.C. circuit, is called *inductive reactance*. (Essentially the same effect is also produced in a pulsating D.C. circuit.)

Inductive reactance is expressed as follows:

$$X_L = 2\pi fL$$

where

X_L = *Inductive reactance in ohms*

$2\pi = 6.28$

f = *Frequency in Hz.*

L = *Inductance in henries.*

Other papers of the Course provide a fuller understanding of the effects and behaviour of inductance, capacitance, and resistance in A.C. circuits.

11. TRANSFORMERS – SIMPLE THEORY

11.1 A transformer is a device for transferring electrical energy from one A.C. (or varying D.C.) circuit to another, using the principle of mutual induction in a common magnetic circuit. It consists essentially of two insulated windings, termed *primary* and *secondary*, wound on a core of laminated iron or similar high permeability material.

When an alternating (or varying) e.m.f. is applied to the primary, a higher or lower alternating voltage is available from the secondary. When the voltage at the secondary is higher than that applied, the transformer is said to be a *step-up* transformer; when it is lower it is a *step-down* transformer.

11.2 CONSTRUCTION. Fig. 37 shows some basic transformer designs.

The shell type (Fig. 37d) is the one most commonly used, as its design is more efficient, with less magnetic losses than the other types shown.

11.3 BASIC PRINCIPLE. The principle of the transformer is that of mutual induction. The A.C. (or varying D.C.) in the primary coil sets up a varying magnetic flux in the magnetic circuit. This variation of flux results in an induced alternating e.m.f. in the secondary circuit, having the same frequency as the applied current.

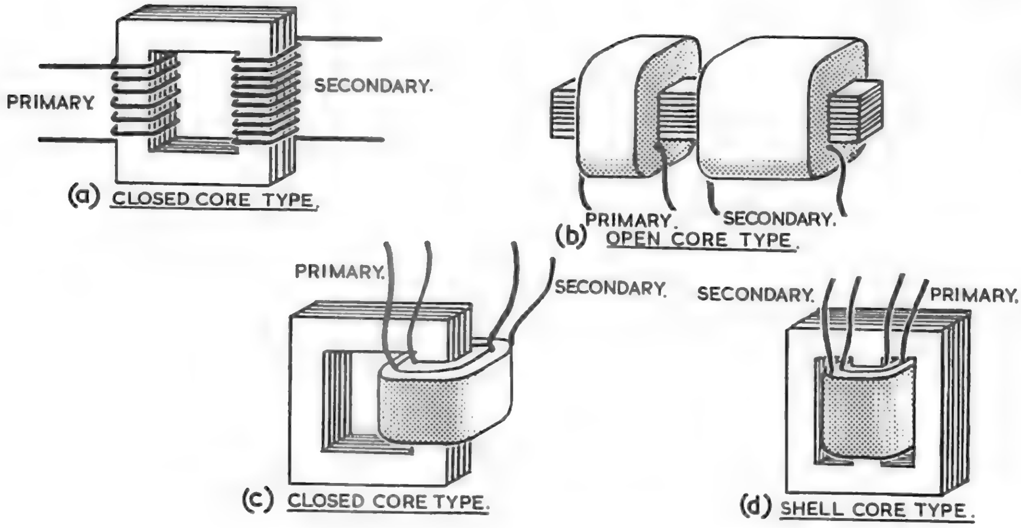


FIG. 37. TYPES OF TRANSFORMERS.

11.4 VOLTAGE TRANSFORMATION. Let us consider a transformer with 100 primary turns, and 200 secondary turns (Fig. 38).

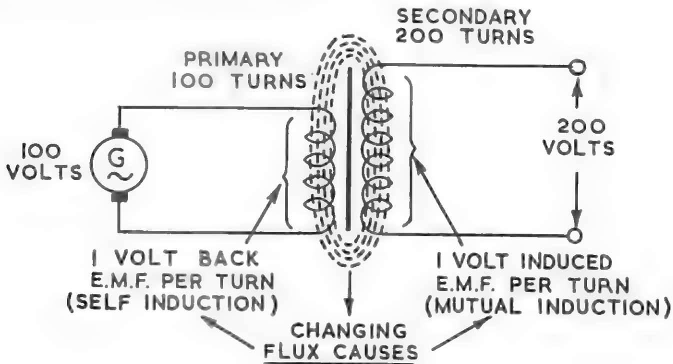


FIG. 38. STEP-UP TRANSFORMER.

An alternating potential of 100 volts is applied to the primary winding, and the secondary winding is left open circuit. Current flows in the primary winding and an alternating flux is established in the core. The flux links the turns of both windings inducing an e.m.f. of self induction in primary winding and an e.m.f. of mutual induction in the secondary.

In a well designed transformer, the voltage of self induction so closely approximates the applied e.m.f., that we can consider that the induced e.m.f. equals the applied e.m.f. We may assume then that the induced e.m.f. of the primary is 100 volts, that is, the magnetic field induces an alternating e.m.f. of 1 volt per turn in the primary winding, in opposition to the applied e.m.f.

In Fig. 38, the secondary winding is placed in such a manner that the flux produced by the primary winding links the turns of the secondary.

Now the flux, which is in this case inducing an e.m.f. of self induction of 1 volt per turn in the primary, is also linking the secondary and, therefore, will induce an *e.m.f. of mutual induction* (in the same direction as the induced e.m.f. of the primary) of 1 volt per turn in the secondary.

As the secondary has 200 turns, the voltage of mutual induction will be 200 volts.

If the secondary winding had 500 turns, the voltage would be 500 volts and so on.

In other words, the ratio of primary voltage (Ep) to induced secondary voltage (Es) is equal to the ratio of primary turns (Np) to secondary turns (Ns).

That is - $\frac{Ep}{Es} = \frac{Np}{Ns}$ or $Es = Ep \times \frac{Ns}{Np}$

11.5 In transformer theory, the ratio of secondary turns to primary turns $(\frac{Ns}{Np})$ is called the turns ratio (or transformation ratio)(symbol T).

Thus, for voltage transformation:

$Es = T\ Ep$ where

Ep = *Primary voltage*

Es = *Secondary voltage*

T = *Turns ratio*

11.6 **CURRENT TRANSFORMATION.** Now let us consider a transformer with 200 primary turns and 100 secondary turns connected to a 200 volts supply (Fig. 39).

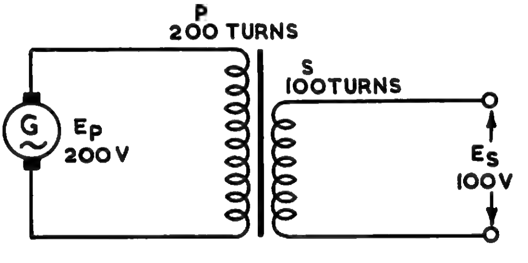


FIG. 39. STEP-DOWN TRANSFORMER.

The changing magnetic flux which induces an e.m.f. of self induction of 200V across the primary, or 1 volt per turn, will induce 100 volts across the secondary winding.

When a 50 ohms load resistance is connected across the secondary the resulting current will be:

$$I = \frac{E}{R}$$

$$= \frac{100}{50}$$

$$= 2 \text{ amperes.}$$

Neglecting Losses, the power output from the secondary will be -

$$P = E \times I$$

$$= 100 \times 2$$

$$= 200 \text{ watts.}$$

As the power output comes from the source of supply, that is, the primary circuit, the power input must be (neglecting losses) 200 watts. Therefore, the primary current is:

$$I = \frac{P}{E}$$

$$= \frac{200}{200}$$

$$= 1 \text{ ampere.}$$

From this, the ratio of currents in the primary and secondary, is the inverse of the turns ratio.

Neglecting losses, this can be expressed mathematically as follows:

$$Ep\ Ip = Es\ Is$$

$$\text{or } \frac{Is}{Ip} = \frac{Ep}{Es} = \frac{Np}{Ns}$$

$$\therefore Is = \frac{Ip}{T} \quad \text{where} \quad \begin{aligned} Ip &= \text{Primary current} \\ Is &= \text{Secondary current} \\ T &= \text{Turns ratio.} \end{aligned}$$

11.7 IMPEDANCE TRANSFORMATION. Besides transforming voltages and currents, an important use of the transformer is that of impedance transformation.

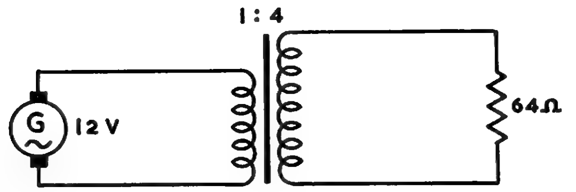
Impedance, as we shall see fully in other papers of the course, is the total opposition to current flow in alternating current circuits, and takes into account the circuit's resistance, inductive reactance, and capacitive reactance.

When a source of supply is working into a load, such as a generator energising a bell, or a telephone transmitter working into the line and the instrument at the far end, maximum power is transferred from the source of supply to the load, when the impedance of the supply equals that of the load.

This is often achieved by using a transformer which *"matches"* the two impedances. For example, the induction coil (a form of transformer) in the circuit of a telephone, matches the telephone transmitter to line and far instrument for efficient transmitting, and matches the receiver to line and far instrument for efficient reception. Such matching is necessary, because in telecom. powers of a few milli-watts are quite common.

11.8 Where the A.C. generator and load impedances are unequal and maximum power is required in the load, the transformer is used to match the generator and the load.

Consider an A.C. generator which develops 12 volts across its terminals whilst supplying power to a load resistance of 64 ohms, via a step up transformer having a turns ratio of 4.



Primary Voltage E_p *= 12 volts*

Secondary Voltage E_s *= 48 volts*

∴ Load Current I_s *= 0.75 amperes*

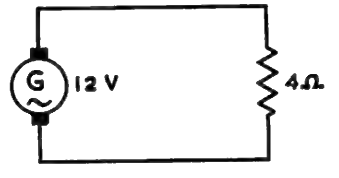
and Power in Load P_s *= 36 watts*

Assuming no Losses - Primary Power P_p *= 36 watts*

∴ Primary Current I_p *= 3 amperes.*

Since I_p *= 3 amperes and* E_p *= 12 volts, then the effective load on the generator = 4 ohms.*

We can therefore derive an equivalent circuit for the generator load:



From this example we can see, that due to the action of the transformer, the 64 ohm secondary load is *reflected* back from the secondary to the primary circuit, and appears as an equivalent load of 4 ohms.

If we assume the resistance of the generator as 4 ohms, then maximum power is transferred from the generator to the load via the impedance matching transformer.

11.9 The ratio of load to reflected resistance corresponds to the square of the turns ratio, that is:

$$\frac{64}{4} = T^2. \ (16).$$

The impedance transformation ratio of a transformer can be found from:

$$T^2 = \frac{Z_s}{Z_p}$$

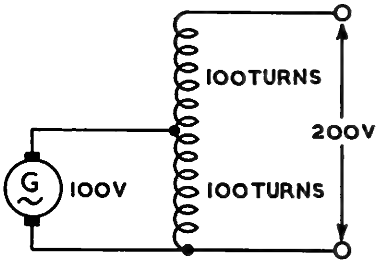
where

T = *Turns ratio*

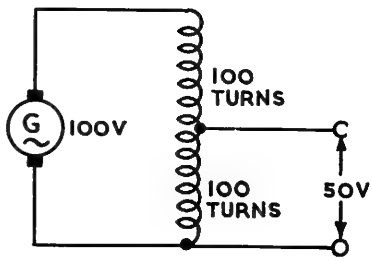
Z_s = *Load impedance of secondary*

Z_p = *Impedance offered by primary to supply under load conditions.*

11.10 AUTO-TRANSFORMER. In the conventional transformer, the primary and secondary windings are electrically separate, but in the auto-transformer the secondary winding is connected to the primary winding (Fig. 40), the whole forming a single winding with appropriate tappings. When the primary winding forms part of the secondary winding it is a step-up transformer (Fig. 40a); when the secondary forms part of the primary winding, it is a step-down transformer (Fig. 40b).



(a) Step-up.



(b) Step-down.

FIG. 40. AUTO-TRANSFORMER.

For all practical purposes the auto-transformer is the same in its magnetic action, and can be used for exactly the same purposes, as an equivalent two winding transformer; that is, for voltage, current, and impedance transformation.

11.11 TRANSFORMER LOSSES. Although the transformer is the most efficient of all electrical devices, with efficiencies of above 95% not uncommon, its efficiency is reduced by losses in the winding and in the core.

Winding loss is sometimes called *copper loss* or *I^2R loss* and is due to loss of electrical energy in the windings of the transformer due to their resistance; this appears in the form of heat.

Core losses occur for a number of reasons as follows.

- MAGNETIC LEAKAGE occurs when lines from one energised winding do not link or cut the other winding. The effect of magnetic leakage is to reduce the secondary voltage for a given primary voltage.

  To overcome magnetic leakage, the transformer coils are wound one on another, and an efficient magnetic circuit used.

- HYSTERESIS LOSS refers to the energy lost in reversing the direction of magnetisation within the core material with each alternation; this appears in the form of heat. This loss is reduced by using a special core material such as silicon steel or permalloy in which the effect of hysteresis is not marked.

- EDDY CURRENTS. Let us consider the magnetic action in a transformer with a solid soft iron core. The core is actually a single turn secondary winding of very low resistance which has a low value of voltage induced in it by the varying magnetic field.

  As the direction of induction is at right angles to the main field, circular currents of a large value flow in the core (Fig. 41a). These currents, called *"eddy currents"*, as well as possessing a field in opposition to the main field, also cause a considerable loss of energy in the form of heat in the core.

11.12 To overcome the effect of eddy currents, the core is constructed of thin laminations, each one insulated from the next by oxide or varnish, and bolted tightly together to prevent vibration caused by the changing magnetic field (Fig. 41b).

(a) Solid Core. (b) Laminated Core.

FIG. 41. LIMITING EDDY CURRENTS.

By using laminations, the core is continuous in the direction of the field, but is broken up into many high resistance paths for the eddy currents.

To further decrease the effect of eddy currents, core materials of high electrical resistance with high permeability, such as silicon steel and permalloy, are used.

NOTES

12. TEST QUESTIONS

1. *Name the essential difference between permanent magnets and temporary magnets.*

2. *What is meant by the term, magnetic field?*

3. *Draw typical patterns for the magnetic fields of:*

   (a) a bar magnet;
   (b) a horseshoe magnet.

4. *State the laws of magnetism.*

5. *Briefly describe the process by which a piece of iron is attracted to a magnet.*

6. *Draw a simple labelled diagram showing how an item of equipment can be shielded from a magnetic field.*

7. *State the rule for determining the direction of the magnetic field surrounding a current-carrying conductor.*

8. *Draw a simple sketch showing the magnetic field produced when current flows in:*

   (a) a single loop of wire;
   (b) a solenoid.

9. *State the rule for determining the magnetic polarity of a solenoid.*

10. *What is meant by the terms:*

    (a) flux density?
    (b) magnetising force?

11. *Name and state the relationship of the factors which determine the reluctance of a sample of magnetic material.*

12. *Draw a typical B/H curve for a magnetic material, and briefly describe the process of magnetisation of iron.*

13. *Sketch a typical hysteresis loop and on it indicate the points which correspond with:*

    (a) saturation;
    (b) remanence;
    (c) coercive force.

14. *What is meant by the term hysteresis as applied to ferromagnetic materials?*

15. *Draw simple hysteresis loops of materials which have:*

    (a) small hysteresis loss;
    (b) large hysteresis loss.

16. *State the essential magnetic characteristics of:*

    (a) a soft magnetic material;
    (b) a hard magnetic material.

17. *Name two advantages of ferrites as compared with iron, for use in the cores of devices which operate at high frequencies.*

TEST QUESTIONS (CONTD.)

18. *State Faraday's Law of electromagnetic induction.*

19. *Describe two simple experiments illustrating this law.*

20. *An induced e.m.f. will occur when:*

    (i) ....
    (ii) ....
    (iii) ....

21. *The value of the induced e.m.f. depends on:*

    (i) ....
    (ii) ....
    (iii) ....

22. *Describe a method by which the relationship between direction of motion, direction of field, and direction of induced current, may be determined.*

23. *What is meant by Lenz's Law?*

24. *Describe the principle of the A.C. generator, using diagrams to illustrate your answer.*

25. *The iron core of the generator's armature increases the value of induced e.m.f. by increasing the* ....

26. *Describe fully why a telephone generator is hard to turn when a short circuit is placed on its output terminals.*

27. *Briefly explain the principles of a D.C. generator.*

28. *In generator theory what is meant by:*

    (i) separate excitation;
    (ii) self excitation.

29. *List 3 types of self excited generators.*

30. *Parallel current-carrying conductors experience mutual forces of* .... *or* .... *depending upon whether the currents are* ....

31. *Using diagrams to illustrate your answer, describe the "motor principle" of a current-carrying wire in a magnetic field.*

32. *Describe the left hand rule for motors.*

33. *Briefly describe the operation of a simple motor under:*

    (i) no load conditions;
    (ii) full load conditions.

34. *What is meant by:*

    (i) mutual inductance;
    (ii) self inductance?

35. *Define the unit of inductance.*

36. *How can coil windings be made non-inductive?*

TEST QUESTIONS (CONTD.)

37. *Briefly describe the construction of a transformer.*

38. *Describe the simple operation of a:*

    (i) step-up transformer;
    (ii) step-down transformer.

39. *In transformer theory, the ratio of secondary to primary turns is called .... with the symbol ....*

40. *For voltage, current and impedance transformation, the following formulas should be used:*

    (i) ....
    (ii) ....
    (iii) ....

41. *What is an auto-transformer?*

42. *In transformer theory, what is meant by "winding loss"?*

43. *How does magnetic leakage affect the efficiency of a transformer?*

44. *(i) What is the action and effect of hysteresis loss in a transformer?*
    (ii) How is this loss reduced?

45. *Sketch and describe the effects of eddy currents in a transformer.*

END OF PAPER.